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Fuel Moisture as Measured and Predicted During the 1988 Fires in Yellowstone Park

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ABSTRACT

Fine fuel moisture content, relative humidity, air temperature, and fire behavior were observed hourly for 48 hours on the North Fork Fire in Yellowstone National Park from August 25 to August 27, 1988. Fine fuel reached minimum moisture contents of 3 to 5 percent late in the afternoon, remained below 8 percent until after midnight, then rose to a maximum of 10 to 11 percent around 9 a.m. At this time, fires were burning actively well into the night, subsiding to low-intensity surface and ground fire during the morning, then entering the crowns in late afternoon. Live foliage moisture contents were sampled predawn and late afternoon. Standing dead boles, duff, and mineral soil were also sampled. Moisture contents were determined by Computrac moisture analyzer, ovendrying, and Delmhorst wood moisture meter. Measured fine fuel moisture contents were compared with those predicted by fire behavior analysts' tables and the BEHAVE fire prediction system.

KEYWORDS: wildfire, diurnal weather, Yellowstone National Park, weather, fire behavior

In mid-August of 1988, the behavior of fires in the Greater Yellowstone Area surpassed that predicted in early August by a six-member team of fire specialists (Rothermel 1990). Projected growth of the fires was based on previously observed fire behavior in specific fuel types within the park and most probable expected weather for the season. Extended drought conditions and the repeated passage of dry cold fronts, which brought strong gusty winds and no appreciable precipitation, created the conditions for fire growth beyond projections. Crown fires, which had previously been limited to areas of decadent lodgepole pine (*Pinus contorta* Dougl.), continued to spread regardless of fuel type or stand age. In addition, the daily burning period was extending as the season progressed so that by mid-August fires were burning actively, even crowning, well into the night. In late August a team was called in from the Intermountain Fire Sciences Laboratory (IFSL) by the Greater Yellowstone Area Command. The team monitored fine fuel moisture content hourly for a 48-hour period to help explain the extended active burning period. These data were used promptly after collection to explain the persistence of the fires and why fire control actions taken at night were not effective. This paper discusses these observations and compares the observed moisture contents with predictions for those conditions.

FUEL MOISTURE SAMPLING

Three sites were sampled near the west flank of the North Fork Fire (fig. 1) within fuels representative of those consumed by the fire. They were situated in the path of the North Fork Fire, near the road between West Yellowstone and Madison Junction, from 3 to 6 miles east of West Yellowstone. Fire activity in the area prevented the team from remaining at one site for the duration of the study. The fire burned over all three sites within hours to a few days after sampling. Though location differed, canopy cover, aspect, elevation, and proximity to the Madison River were essentially the same between sites. All sites were flat benches with 30 to 60 percent canopy cover, primarily lodgepole pine, with occasional Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). The understory vegetation was

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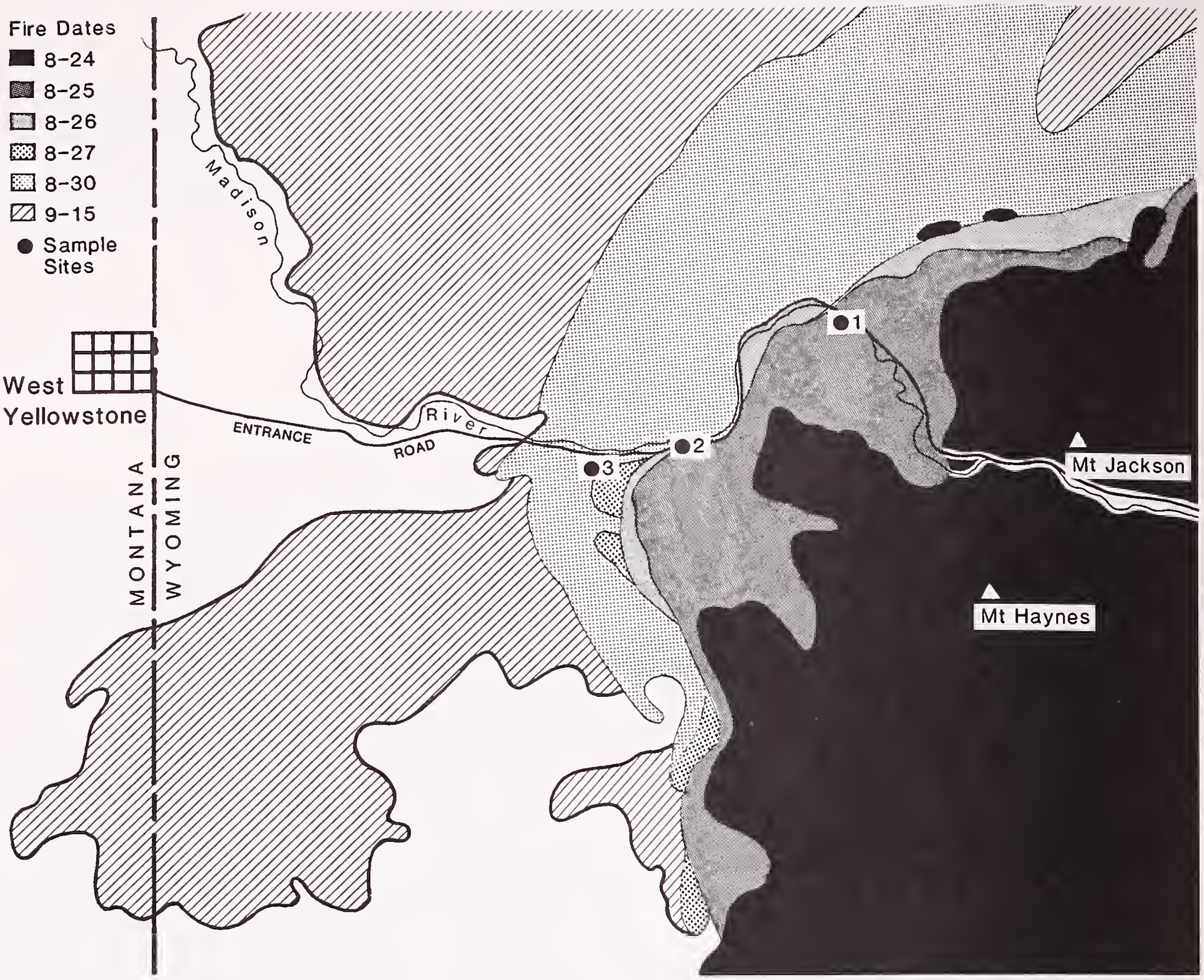

Figure 1—West flank of the North Fork Fire indicating numbered sample sites and fire perimeters just prior to, during, and immediately following the study, and final perimeter.

sparse grass, with juniper (*Juniperus* spp.), big sagebrush (*Artemesia tridentata*), and grasses in the openings.

Three composite samples from the loose upper litter under lodgepole pine canopy were collected in 4-inch-diameter soil cans approximately hourly for 48 hours. The litter consisted primarily of lodgepole pine needles cast in the past year, but also contained bark flakes, twigs less than one-fourth inch in diameter, and cones. After each sampling period, one sample was evaluated on site with a Computrac[2] moisture analyzer powered by a portable generator. The other two samples were sealed and their moisture contents determined later by drying in a convection oven at 217 °F (103 °C). Temperature, relative humidity (table 1), eye-level windspeed, and current fire behavior near the site were recorded at the time of sample collection.

Incidental samples were also taken to characterize the moisture status of other fuels in the area. Dead grass was not collected hourly because it was a very minor component of the surface fuel complex within the forested sites that were burning, but was collected at predawn and midafternoon to obtain measurement of the approximate maximum and minimum values reached in this fine fuel. Duff and mineral soil samples were collected as well as predawn and midafternoon live foliar moisture samples from conifers and shrubs. The moisture content of dead standing and downed large-diameter (3+-inch) boles were measured using a Delmhorst wood moisture meter.

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[2] The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1—Weather and litter fuel moisture observations

Date	Time	RH	Temp	Fine fuel moisture	Date	Time	RH	Temp	Fine fuel moisture
		Pct	*°F*	*Pct ovendry*			*Pct*	*°F*	*Pct ovendry*
August 25	4:00 p.m.	9	88	3.2	August 26	4:00 p.m.	8	80	5.3
	4:40 p.m.	10	82	3.5		—	—	—	—
	5:00 p.m.	11	88	4.1		5:00 p.m.	9	77	5.2
	5:20 p.m.	12	88	5.3		—	—	—	—
	6:00 p.m.	10	89	5.4		6:00 p.m.	20	69	4.8
	6:20 p.m.	11	83	5.1		—	—	—	—
	7:00 p.m.	12	81	5.5		7:10 p.m.	28	65	5.6
	8:00 p.m.	20	67	5.6		8:00 p.m.	34	60	5.5
	9:00 p.m.	21	78	5.7		9:00 p.m.	38	56	6.0
	10:30 p.m.	32	68	6.3		10:30 p.m.	45	52	7.0
	11:00 p.m.	30	68	6.4		11:00 p.m.	54	48	7.1
August 26	Midnight	42	59	6.1	August 27	Midnight	60	43	7.5
	1:00 a.m.	46	54	6.8		1:00 a.m.	66	39	8.3
	2:00 a.m.	49	53	6.8		2:00 a.m.	72	39	8.0
	3:00 a.m.	48	50	7.5		3:15 a.m.	64	37	8.5
	4:00 a.m.	56	42	7.8		4:00 a.m.	72	33	9.2
	5:00 a.m.	62	38	8.1		5:00 a.m.	83	30	9.0
	6:00 a.m.	64	35	7.9		6:00 a.m.	79	30	8.9
	6:30 a.m.	74	43	9.6		—	—	—	—
	—	—	—	—		7:00 a.m.	73	33	8.9
	8:30 a.m.	48	60	10.5		8:40 a.m.	65	46	9.5
	9:00 a.m.	46	59	10.7		9:00 a.m.	66	45	10.3
	10:00 a.m.	36	63	9.3		10:15 a.m.	46	58	10.3
	11:00 a.m.	16	76	8.9		11:00 a.m.	41	58	9.9
	Noon	15	75	7.2		Noon	30	64	8.7
	1:00 p.m.	12	78	7.0		1:00 p.m.	25	69	7.4
	2:00 p.m.	12	78	6.1		2:00 p.m.	18	72	7.2
	3:15 p.m.	9	81	5.5		3:00 p.m.	15	73	7.1
	4:00 p.m.	8	80	5.3		4:00 p.m.	13	80	6.4

WEATHER AND FUEL MOISTURE OBSERVATIONS

The weather in the area had been dominated by a high pressure ridge during the week, with warm afternoon temperatures in the upper 80's, extremely low relative humidities, and morning inversions. On August 25, the high pressure ridge began to weaken and move eastward allowing cooler air to move in along with a slight increase in moisture. Upper level winds were west to southwest at 10 to 15 mi/h during the afternoon. One thunderstorm developed the evening of the 25th over the fuel moisture site delivering a trace of rain. A smokey inversion persisted until around 11 a.m. on the morning of the 26th. Late on the 26th a dry cold front brushed the park bringing stronger northwest to north winds aloft at 15 to 25 mi/h and a slight increase in relative humidity. Dense smoke remained over the sample site into early afternoon on the 27th with cooler temperatures. Skies were clear to partly cloudy throughout the period with cumulus buildups in the afternoons over the smoke columns and up to 40 percent cloud cover for a few hours the night of the 25th.

The litter fuels collected during the study were shaded most of the time by the lodgepole pine canopy. Under the canopy, fuels received direct solar radiation only for relatively short periods of time as the shadows and sunspots were continually shifting. These fuels were also well sheltered from the wind. There was no wind at the surface while the inversion was present. After the inversion lifted, eye-level windspeeds of 3 to 5 mi/h, with occasional gusts to 7 to 10 mi/h in the afternoon, were observed. The wind subsided at dusk.

Both methods of litter moisture analysis gave comparable results for the range of moisture contents observed. The Computrac proved to be a valuable tool for rapidly evaluating dead fuel moisture contents on site. Differences between paired samples dried in the oven were as great as

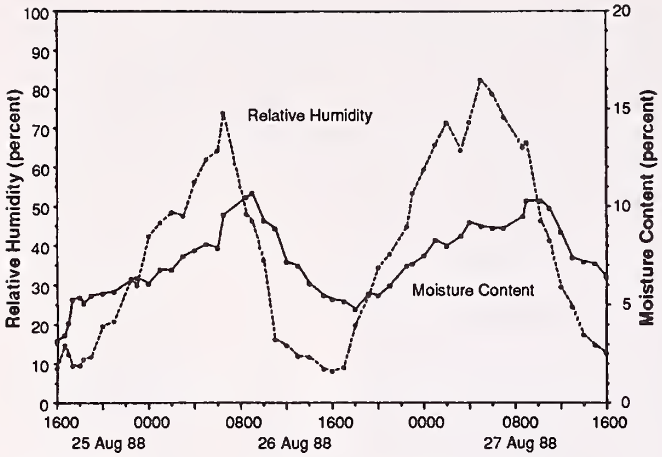

Figure 2—Diurnal trend of observed relative humidity and measured moisture content in lodgepole pine litter, August 25 to 27, 1988.

differences between the ovendry and Computrac-measured moisture. A variability of up to 2 percent moisture content was observed both in the oven-dried pairs and between the two techniques, but the average difference was only 0.5 and 0.75 percent moisture content, respectively. These differences are within expected variability in field-collected samples.

An average moisture content (table 1), calculated for each sampling period from all litter samples, was used for further analysis. All moisture contents are expressed as a percentage of the dry weight.

Figure 2 displays the relative humidity and fine fuel moisture during the 48-hour sampling period. Moisture values under 4 percent were observed in shaded litter fuels in late afternoon; unshaded fine fuels reached this value by early afternoon. A thermocouple placed just under the surface-most needle litter registered approximate surface fuel temperatures. Fuel temperatures as high as 128 °F were measured in these unshaded fuels. The litter moisture content remained low, between 5 to 7 percent until after midnight. The highest moisture contents observed in the litter, around 11 percent, occurred about 9 a.m. This 11 percent moisture content is well below the moisture of extinction of these fuels, which would range from 18 to 25 percent. By comparison, standing cured grass moisture content ranged from 4 to 7 percent in the afternoon to 13 to 18 percent just before dawn.

Moisture contents in longer response fuels were also very low. Large-diameter sound dead wood ranged in moisture from 4 to 9 percent, with the higher moistures occurring in boles with bark. Most boles measured 6 to 7 percent. Duff moisture content ranged from 8 to 12 percent in shaded areas where the duff had accumulated to a depth of 4 inches or more. Duff in unshaded areas, and areas with thin accumulations of duff, had moisture contents similar to that of the litter layer. Mineral soil moisture content at the interface between soil and duff was only 3 to 4 percent.

Live conifer foliar moisture contents were similar to those observed in other conifer species at that time of year. The measured moisture of mature conifer needles ranged from 96 to 118 percent and new needles ranged from 117 to 148 percent. Lodgepole pine foliage sampled in 1989 and 1990 in Yellowstone National Park ranged from 95 to 146 percent, averaging about 120 percent in late August (unpublished data on file at IFSL). This compares with mature needle moisture contents of Douglas-fir and ponderosa pine (*Pinus ponderosa* Laws.) of 110 to 120 percent in mid-August and new needle moisture contents averaging 130 percent (Philpot and Mutch 1971). Philpot and Mutch found that the general trends in foliar moisture were similar from one year to the next even though weather differed. Johnson (1966) observed the seasonal trend of foliar moisture content in red pine (*Pinus resinosa* Ait.) and jack pine (*Pinus banksiana* Lamb.), reporting mature needle moisture contents in the range of 110 to 125 percent and new needle moisture contents between 125 and 150 percent in late summer. Jack pine foliar moisture contents were measured by Crosciewicz (1986) over two seasons. Old foliage ranged from 95 to 110 percent, and new foliage was near 150 percent in late summer.

Measured moisture contents of shrub foliage were considerably lower than those of the conifers, but were within the range expected for that time of year. Moisture content in sagebrush ranged from 78 to 106 percent. By comparison, Wyoming big sagebrush (*Artemesia tridentata wyomingensis*) moistures measured at the Dinosaur National Monument in 1987 and 1989 ranged broadly in late August from 50 to 105 percent, averaging 60 to 80 percent (Riedel and Petersburg 1989). Sagebrush moisture contents measured in 1989 in southeastern Montana ranged from 67 to 110 percent, and those measured in 1990 in Yellowstone National Park (unpublished data on file at IFSL) averaged around 110 percent in late August.

Observed fire behavior ranged to dramatic extremes throughout the diurnal sampling period. At 2 p.m. on August 25 large smoke columns capped by cumulus clouds were visible from West Yellowstone. At 4 p.m. the fire was observed moving through the surface fuels and the crowns from the south toward the Madison River. A spot fire ignited on the hillside across the river, a jump of at least one-fourth mile, and trees began torching within minutes. The team was requested to move back toward West

Yellowstone as the fire was approaching the highway and would be crossing it. At 8 p.m. a crown fire was observed approaching from the south with flame heights to about 150 feet. The crown fire was observed until 9:30 p.m. when it was again necessary to relocate. At 11 p.m. surface fuels were burning, with flame heights of 2 to 5 feet, in sagebrush at an estimated 2 chains per hour rate of spread. Smaller lodgepole pine and pine near fuel jackpots continued to torch. Intense burning to the east was noted by the smoke column and strong orange glow on the horizon. By 2:30 a.m. August 26, flame lengths through the needle litter were 3 to 4 inches in a continuous front, 6 inches in dead grass, and 2 feet in sagebrush. Burning was primarily limited to the surface fuels. Flames climbed tree boles but did not ignite the foliage. The surface fire burned through the bases of the standing lodgepole pine, with numerous trees falling throughout the night and early morning at a rate of one to two per minute in the immediate area. Intensity increased and waned both to the north and to the east of the sample site, subsiding just before dawn. Predawn flame heights were 6 inches to 1 foot in litter and small downed dead fuels, up to 4 feet in larger concentrations of fuel.

From 6 to 8 a.m. the surface fire burned well in the litter, with flame heights of 3 to 4 inches. The fire continued to burn strongly at the bases of trees, climbing the boles but not igniting the crowns. By 9 a.m., flame heights were down to 2 to 4 inches in the litter and by 9:30 a.m., the litter was only smoldering. The sun began to feel effectively warm around 10 a.m., and the litter began flaming again with flame lengths up to 6 inches. Smoke columns began building east and south of the sample area. By 11 a.m. flame lengths in litter were up to 1 foot, and flame lengths of 3 feet were observed in downed woody material. By noon, torching of individual and small groups of trees was observed. From 1 to 3 p.m., fire across the river from the site was carried through the lodgepole pine crowns, but adjacent to the sample site flames remained on the surface, with occasional torching within the heavily canopied area.

A burnout operation at 8 p.m. produced frequent torching and illuminated the sky until 4 a.m. the morning of August 27. At 4 a.m., flaming in the fine fuels continued with lengths of 4 to 6 inches. By 6 a.m., flame fronts were no longer continuous and by 8 a.m. flaming was replaced by smoldering. The inversion persisted throughout the morning, with little increase in fire activity until around 2 p.m. By 3 p.m. cumulus clouds were building over smoke columns to the east of the site.

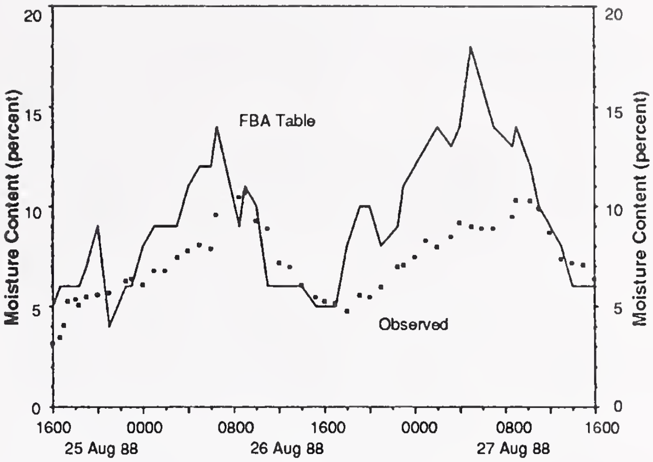

Figure 3—Comparison of observed (points) and predicted (curve) fine fuel moistures. Predictions obtained from the FBA tables.

EVALUATION OF PREDICTED MOISTURE CONTENTS

The weather parameters collected during the fuel moisture sampling period were used to calculate expected fine fuel moisture contents. Two methods of prediction were tested. The fire behavior analyst (FBA) tables, as described by Rothermel (1983), allow moisture content calculation at any specified time based on observed relative humidity and temperature. The MOISTURE module of FIRE2 of the BEHAVE prediction system (Andrews and Chase 1989) incorporates the moisture model developed by Rothermel and others (1986). This model predicts hourly temperature, relative humidity, and fuel moisture content based on the input of weather conditions at specified times.

Figure 3 includes observed moisture contents and those calculated using the FBA tables. Shaded daytime conditions were assumed because of the combination of canopy cover and smoke. Using the tables, each prediction is based on the actual relative humidity and temperature observed at the time of sampling. No provision is given for a time lag in moisture recovery. Also, at 8 p.m., moisture prediction begins from the nighttime tables. The abrupt drop in predicted moisture content at this time is due to differences between the daytime and nighttime tables. The daytime minimum moisture contents used to predict fire behavior during normal burning times are very close to actual moisture contents. The predicted nighttime fuel moisture contents are higher than observed in lodgepole pine litter and peak moisture contents correspond with peak relative humidity observations.

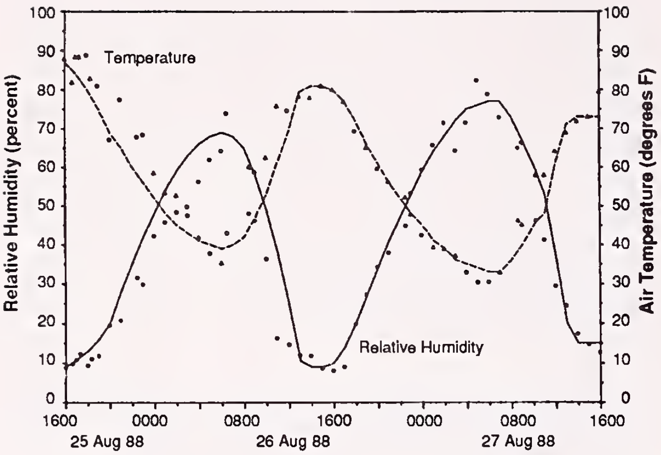

Figure 4—Comparison of observed (points) and predicted (curves) relative humidity and air temperature. Predictions obtained from MOISTURE module of FIRE2 in BEHAVE.

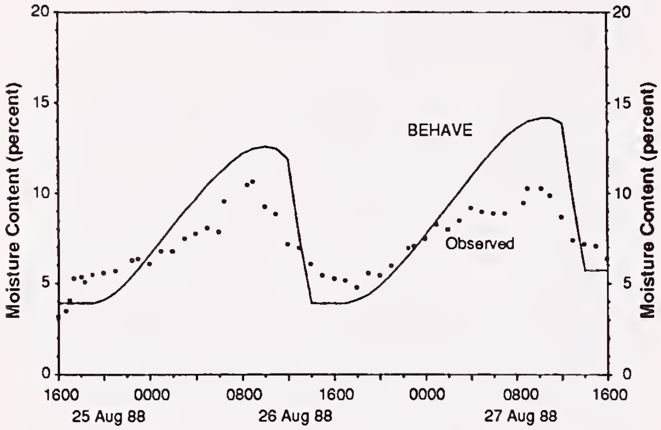

Figure 5—Comparison of observed (points) and predicted (curve) fine fuel moisture. Predictions obtained from MOISTURE module of FIRE2 in BEHAVE.

The MOISTURE module of BEHAVE can be used to provide a diurnal cycle of weather and fine fuel moisture content predictions at hourly intervals. Temperature and relative humidity are input at 2 p.m. (the day prior to burn day), sunset, sunrise, and at burn time. For this comparison, burn time was set at 11:59 a.m. Hourly predictions were obtained from noon on burn day–1 through 11:59 a.m. on burn day. This procedure was followed to obtain predictions for August 25, 26, and the morning of August 27. To obtain predictions for the balance of the 27th, weather conditions were input for 2 p.m. on burn day and at the burn time of 4 p.m. The BEHAVE prediction of relative humidity and air temperature was quite close to observed values (fig. 4). The predictions of fine fuel moisture content (fig. 5) were good during the afternoon and for the period through the night of August 25. On the night of the 26th and morning of the 27th, however, the moisture of the litter fuels recovered only to the same level as on the previous night, though it was predicted to recover an additional 4 percent due to the higher relative humidity that second night. Through both diurnal periods, the time at which maximum and minimum moisture contents were predicted corresponded with that observed. The abrupt drop in predicted moisture at noon is caused by the transition from one cycle of weather data to the next. The curves illustrate the difficulty of predicting moisture during the night and morning.

DISCUSSION AND CONCLUSIONS

Although the litter fuel moisture content did respond to changes in relative humidity and air temperature, two points are noteworthy. First, the lodgepole pine litter responded differently to rising and falling relative humidity. The fine fuel moisture content began to increase with rising relative humidity within an hour after reaching the afternoon low point; however, its recovery rate was slow. The maximum fuel moisture was reached 3 to 4 hours after the peak in relative humidity. Therefore, the rate at which moisture was gained by the fuel was slower than the rate at which it was lost. Secondly, the litter fuels did not recover to their moisture-of-extinction levels of 18 to 25 percent. The nighttime relative humidity reached 74 percent by morning of August 26 and 83 percent the following morning. Based on the temperature and relative humidity at the sample sites, fine fuel moistures were predicted to reach 13 to 14 percent by early morning of the 26th and 14 to 18 percent on the 27th. Fine standing cured grass, sampled at dawn and at 4 p.m., had moisture contents of 13 and 18 percent on the mornings of the 26th and 27th. But, the lodgepole pine litter moisture content reached only 10.7 and 10.3 percent, respectively, those two mornings. There was very little moisture in the system, either in the surrounding air or from the underlying soil, to increase the litter fuel moisture content. The situation, however, was aggravated by the fuel itself. Anderson (1985) showed that the timelag of all fine fuels cannot be assumed to be 1 hour. Conifer needles respond much more slowly, and lodgepole pine was found to be the slowest of the species tested, with a response time of 1.6 hours to more than 34 hours, depending on the degree of decomposition. The needle litter gained moisture at night more slowly than was predicted by the models or measured in the grass.

This minimal fine fuel moisture response in a drought situation is one key to the active nighttime burning that was observed for the Yellowstone fires.

The sample sites were under the influence of inversions by dawn. Fuels on the slopes above the inversion layer may have experienced even less nighttime moisture recovery.

The active crown fire behavior cannot be attributed to unseasonably low foliar moistures. Dead fuels within the crown such as twigs and lichen, however, would have had low moistures similar to those measured in the litter. Also, standing dead large fuels were as dry as the late afternoon values for litter. Dry fuel was readily available to fire from the ground through the crown throughout most of the night and day.

Predictions of fine fuel moisture content based on observed weather yielded expected values in agreement with measured values in dead grass. But after midnight and early morning the predictions were considerably higher than were observed in the fine fuel that was carrying the surface fire, the lodgepole pine needle litter. Observed fire behavior exceeded that expected, especially during the late evening and at night. Fire behavior was consistent with that expected based on the measured fuel moisture contents, which illustrates the value of directly measuring fine fuel moisture content when possible.

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